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16. ABSTRACT The report gives results of an evaluation of an electric curtain for the purpose of particulate control and removal. If the particles are charged by corona, the curtain will stop them only in a very slow air flow (less than 2 cm/sec). At these slow flows, a vertical curtain would stop the particles and a 45-degree curtain would move them along the curtain without penetrating it. A horizontal electric curtain could be used to suspend the particles against gravity. Finally, an attempt to use highly charged water drops as the particle collection mechanism was unsuccessful because of electrical breakdown caused by the water.

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1. INTRODUCTION

The electric curtain can be considered as a device similar in concept to the quadrupole mass spectrometer developed by Paul et al. [1]. Masuda has discussed the action between charged particles and an electric curtain [2]. A planar curtain consists of a set of equally spaced parallel electrodes which are excited by either single phase or six phase ac voltages. The former is designated as the "standing-wave electric curtain" ; the latter, the "traveling-wave electric curtain."

The following experiments were carried out. A planar curtain oriented at 45° with respect to the vertical axis was operated at its optimum single-phase ac voltage against the free-fall of charged particles, such as corona charged lycopodium, silica and feldspar. A horizontal planar curtain was also demonstrated to hold charged particles against gravity when it was energized by a six-phase ac potential. Finally, a vertical planar curtain and corona charging section were connected and sealed together by a wind duct. An air flow mixed with test charged particles was introduced into the system near the corona section end and the motion of the charged particles was examined just in front of the curtain surface.

In all of these three experiments, the curtains were shown to be effective to a certain degree. While three variables in the first two experiments, namely potential on corona wires, particle size, and potential on the electric curtain, needed to be adjusted, in the third experiment the air flow, in addition, had to be controlled to a proper value.

2. THEORY FOR PLANAR CURTAIN REPULSION FORCE ON A CHARGED PARTICLE

Some (4.8 mm) diameter (d) brass rods were placed parallel to each other in the same plane so that the interelectrode spacing was 7.5 mm between nearest rod axes.

This set of brass electrodes was charged by an ac voltage of an angular frequency ω and peak voltage V_0. This voltage generates a repulsion force between the particles and these rods. It is the force which is responsible for suspending the incoming charged particles against other external forces.

By following the method used by Masuda et al. [2], [7] which is the linear approximation of equations of motion using two terms in the potential expansion, an expression for the repulsion force was derived. The periodic potential shown in Figure 1 can be represented by a Fourier expansion, i.e., at $t = 0$,

$$V(x, z) = X(x)\, Z(z) = \sum_{m=1}^{\infty} V_m e^{\frac{-2m\pi}{\lambda} z} \sin\left(\frac{2m\pi}{\lambda} x\right) \quad (m = \text{odd integers}).$$

$$V(x, z) \doteq V_1 e^{\frac{-2\pi}{\lambda} z} \sin\left(\frac{2\pi}{\lambda} x\right) + V_3 e^{\frac{-6\pi}{\lambda} z} \sin\left(\frac{6\pi}{\lambda} x\right)$$

$$V(x, z) \doteq V_1 e^{\frac{-\pi}{a} z} \sin\left(\frac{\pi}{a} x\right) + V_3 e^{\frac{-3\pi}{a} z} \sin\left(\frac{3\pi}{a} x\right).$$

The coefficients V_1 and V_3 are determined by the boundary conditions $V(\frac{a}{2} - r, 0) = V_0$ and $V(\frac{a}{2}, r) = V_0$,

$$V_1 = \frac{\left[\cos\left(\frac{3\pi r}{a}\right) - e^{\frac{-3\pi r}{a}}\right] V_0}{e^{-\pi r/a} \cos\left(\frac{3\pi r}{a}\right) - e^{-3\pi r/a} \cos\left(\frac{\pi r}{a}\right)} \triangleq A\, V_0$$

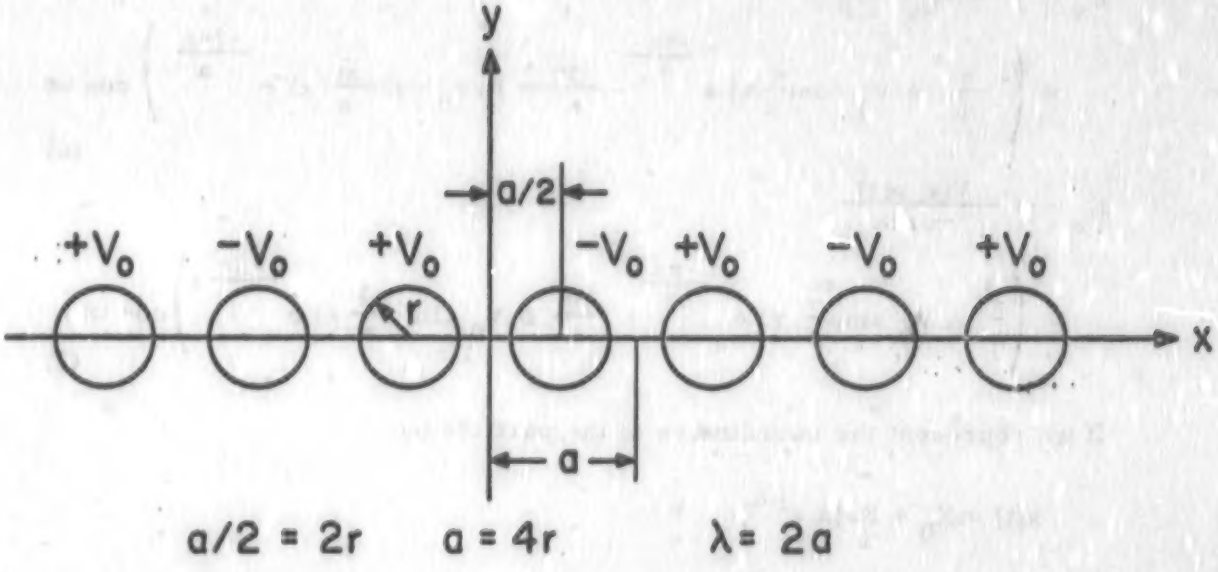


Figure 1. Physical dimensions and the potential of a planar electrostatic curtain.

$$V_3 = \frac{e^{\frac{-2\pi r}{a}}\left(\cos(\frac{\pi r}{a}) - e^{\frac{-\pi r}{a}}\right)V_0}{\cos(\frac{3\pi r}{a}) - e^{\frac{-2\pi r}{a}}\cos(\frac{\pi r}{a})} \equiv B\,V_0 \quad . \tag{4}$$

Therefore,

$$V(x, z, t) = \left(A\,V_0 \sin(\frac{\pi}{a}x) \cdot e^{\frac{-\pi z}{a}} + B\,V_0 \sin(\frac{3\pi}{a}x) \cdot e^{\frac{-3\pi}{a}z}\right)\cos \omega t \tag{5}$$

$$E_x = -\frac{\partial V(x, z, t)}{\partial x}$$

$$= \left(-\frac{\pi}{a}\,A\,V_0 \cos(\frac{\pi}{a}x)\, e^{\frac{-\pi z}{a}} - \frac{3\pi}{a}\,B\,V_0 \cos(\frac{3\pi}{a}x)\, e^{\frac{-3\pi z}{a}}\right)\cos \omega t \tag{6}$$

$$E_z = -\frac{\partial V(x, z, t)}{\partial z}$$

$$= \left(\frac{\pi}{a}\,A\,V_0 \sin(\frac{\pi}{a}x)\, e^{\frac{-\pi z}{a}} + \frac{3\pi}{a}\,B\,V_0 \sin(\frac{3\pi}{a}x)\, e^{\frac{-3\pi}{a}z}\right)\cos \omega t \ , \tag{7}$$

If we represent the coordinates of the particle by

$$x(t) = X_0 + \mathrm{Re}[\hat{x}\, e^{j\omega t}]$$

$$z(t) = Z_0 + \mathrm{Re}[\hat{z}\, e^{j\omega t}] \tag{8}$$

where X_0, Z_0 denote the center of oscillation and $\hat{x}$, $\hat{z}$ represent the oscillation components, the equations of motion are:

$$m\frac{d^2x}{dt^2} = q\,E_x - 6\pi\mu a\,\frac{dx}{dt}$$

$$m\frac{d^2z}{dt^2} = q\,E_z - 6\pi\mu a\,\frac{dz}{dt} \tag{9}$$

where μ is the viscosity of the medium, a is the radius of the charged particle, and the q is the charge on the particle, normally $x << X_0$ $z << Z_0$, so

$$q E_x(x, z, t) \rightarrow q E_x(X_0, Z_0)\ e^{j\omega t}$$

$$q E_z(x, z, t) \rightarrow q E_z(X_0, Z_0)\ e^{j\omega t} \qquad (10)$$

(8), (9), and (10) combine to give

$$\hat{x} = \frac{q E_x(X_0, Z_0)}{-m\omega^2 + j\omega 6\pi\mu a}$$

$$= \frac{q\frac{\pi}{a} V_0 \left(A \cos(\frac{\pi}{a} X_0)\, e^{\frac{-\pi Z_0}{a}} + 3B \cos(\frac{3\pi}{a} X_0)\, e^{\frac{-3\pi}{a} Z_0} \right)(x)}{m^2\omega^4 + 36\pi^2\mu^2 a^2\omega^2} \qquad (x)\ (m\omega^2 + j6\pi\mu a\omega) \qquad (11)$$

$$\hat{z} = \frac{q E_z(X_0, Z_0)}{-m\omega^2 + 36\pi^2\mu^2 a^2\omega^2}$$

$$= \frac{-q\frac{\pi}{a} V_0 \left(A \sin(\frac{\pi}{a} X_o)\, e^{\frac{-\pi}{a} Z_0} + 3B \sin(\frac{3\pi}{a} X_0)\, e^{\frac{-3\pi}{a} Z_0} \right)(x)}{m^2\omega^4 + 36\pi^2\mu^2 a^2\omega^2} \qquad (x)\ (m\omega^2 + j6\pi\mu a\omega) \qquad (12)$$

The time-averaged repulsion force (in z-direction) is then:

$$< F_{rz} > = q < E_z(X_0, Z_0) + (x - X_0) \left.\frac{\partial E_z}{\partial x}\right|_{X_0, Z_0} + (z - Z_0) \left.\frac{\partial E_z}{\partial z}\right|_{X_0, Z_0} >$$

$$< F_{rz} > = \frac{mq^2(\frac{\pi}{a})^3 V_0^2}{2(m^2\omega^4 + 36\pi^2\mu^2 a^2)} \left(A^2\, e^{\frac{-2\pi}{a} Z_0} + 12AB \cos(\frac{2\pi}{a} X_0)\, e^{\frac{-4\pi}{a} Z_0} + 27B^2\, e^{\frac{-6\pi}{a} Z_0} \right) . \qquad (13)$$

A and B as defined in Equations (3) and (4) are functions of the ratio (r/a), thus, the repulsion force on a charged particle is not only a function of peak voltage on the curtain electrodes, the frequency of the voltage, and the charge on the particle but also a function of the geometrical arrangement of the curtain electrodes.

With the arrangement of the brass rods in our curtain, $(r/a) = \frac{1}{4}$, then $A^2 = 4.25$, $12AB = 1.51$ and $27B^2 = 0.1$.

3. THE CHARGER FOR SOLID PARTICLES

The unipolar corona discharge technique, which has been historically proven to be the best method of charging dust particles [5], [6], [3], is the method used in this work. A rectangular corona (negative) section was used to charge various particles during our experiment. It contains ten .28 mm piano wires. The optimum wire-to-wire space that will produce maximum ion current was estimated to be 38 mm. The remaining dimensions of the corona section are length 15.2 cm, width 5.1 cm, and height 42 cm.

If a semiempirically determined value of the critical field is used [3], one could find that a corona onset voltate is about 3.3 kV for this corona box.

An expression formulated by Cooperman [4] can be used to estimate, to a first approximation, the corona current in the duct with the wire(s) charged up to V = 10 kV.

$$i = V(V - V_0)\frac{k}{b^2 \log(4b/\pi a)} \quad \left(\frac{\text{current}}{\text{cm}}\right)$$

where k is the ion mobility, b is the distance between wire and plate, and a is the wire radius. The total corona current of our duct-type charger is then 4.18×10^{-4} A provided the 152.4 cm corona wire has a clean and smooth surface. It is known that the suspended and deposited particles inside the duct may influence the corona. That influence is directly related to the amount and property of the particles.

Ideally, the maximum available corona current for particle charging in the duct-type corona charger of the present configurations is 4.18×10^{-4} A. The charging mechanisms are (a) field-charging process and (b) diffusion-charging process. When particles with diameters larger than 1 μm pass through the discharge space inside the corona charger, mechanism (a) dominates the particle charging. The particles distort the electric field lines such that gas ions traveling along them are intercepted by the particles and the attractive image force will make the gas ions adhere to the particles. For the submicron particles ($d < 0.2$ μm) mechanism (b) is dominant; particles get charged by colliding with ions governed by random thermal motion.

Both (a) and (b) are equally important in charging particles of diameter in the range of 0.2 ~ 1.0 μm.

The particles used in this work were sieved down to No. 400 mesh ($\leq$ 37 μm). Because the particle size and density distributions are unknown, further difficulties will be introduced later.

4. EXPERIMENTAL PROCEDURE AND OBSERVATIONS

A. Inclined Plane Electric Curtain

All experiments were conducted at room temperature except for localised heating due to the ion current in the corona wires. The setup for the first experiment is illustrated in Figure 2. A duct-type corona charger is in the vertical position, and a planar curtain, which is positioned at 45° with respect to the vertical axis, is placed just under the corona box. The test particles, after being sieved through a No. 400 mesh ($\leq$ 37 μm), were fed to the corona charger. The particles were fairly well dispersed after sieving; some of the particles were collected on the plate electrodes while some went through the entire discharge space and fell toward the curtain surface. As the particle-to-curtain-surface distance decreased, the repulsion force on the particle increased, and the effect of the resultant force (gravitational force and the repulsion force) became apparent. Some of the particles were seen to move along the 45° inclined curtain face without touching (see Figure 2), when the electric field strength of the corona was 4 to 5 kV/cm and the curtain was excited just below the breakdown strength. Samples that were tested are (1) lycopodium (2) silica (3) feldspar and (4) flyash (from Detroit Edison). A 30 kV, 5 mA dc power supply was used to energize the corona wires (negative). When the maximum voltage, which corresponds to a field strength of 11 kV/cm, was applied to the corona wires, the minute particle charge produced from the friction between the nylon mesh and the brush made it impossible for these particles to pass across even the very first

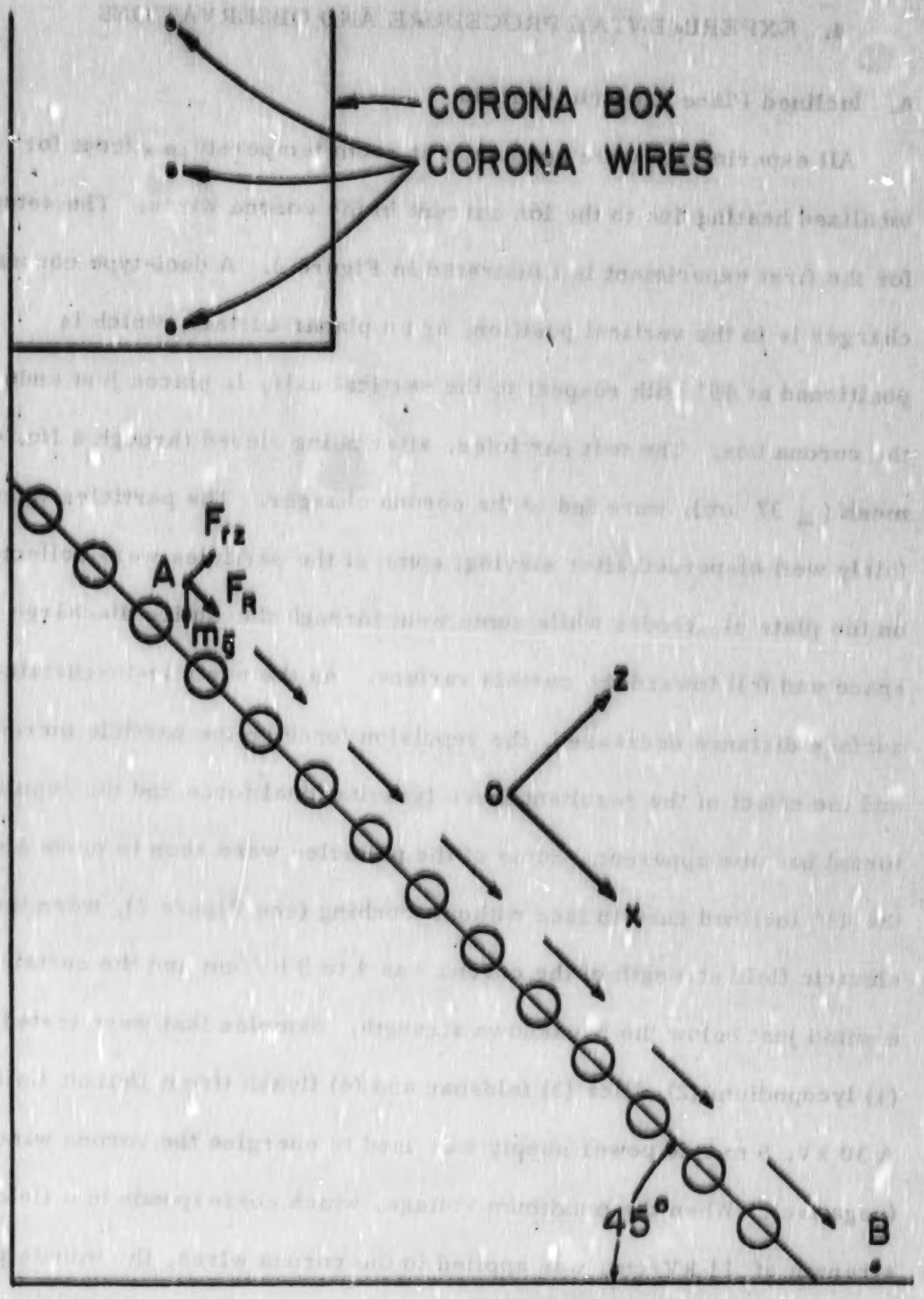


Figure 2. Planar electrostatic curtain positioned at an angle of 45° with respect to vertical axis.

corona wire. Through trial and error, the electric field strength used in this work was then chosen to be 4 - 5 kV/cm. The test sample particles passed the corona charger without being precipitated out on the plate and were observed to fall toward the curtain surface. Some of the particles fell through the curtain as if they were neutral, and some of the particles fell on the rod electrodes. To reduce the effect from the electric field between the corona wire closest to the curtain electrode, the distance between these two highly charged conductors was adjusted to six inches. The effect from the air motion was also eliminated by enclosing the curtain-particle interaction space inside the transparent Plexiglas plates. The accumulation of sample particles near the lower end of the curtain was apparent (near point B in Figure 2).

B. Horizontal Plane Electric Curtain

A horizontal planar curtain was used to suspend charged particles against gravity. Its electrodes were excited by a six-phase ac voltage power supply. The voltage on the curtain was just below the breakdown strength in air. As shown in Figure 3, a duct-type corona charger was also placed in the vertical position and was held above the curtain surface. At the same electric field strength (as described above) in the corona discharge space, the ion density should be around 10^8 - 10^9 ions per cubic centimeter. The corona box acted like an electrostatic precipitator and collected most particles on its grounded aluminum plates. The charging mechanism depended on the particle size of the

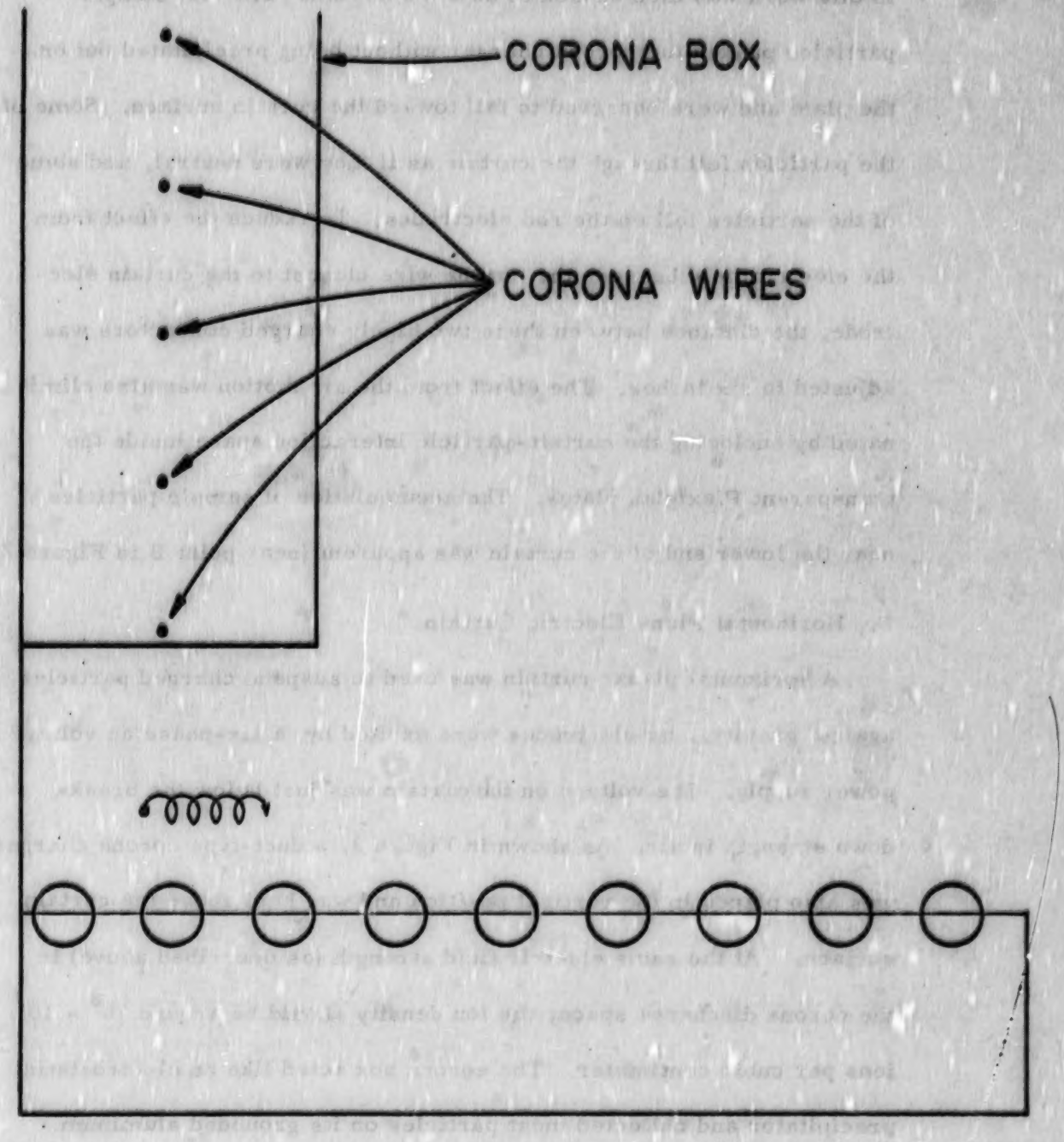


Figure 3. Horizontal planar electrostatic curtain.

test samples (see Section 2). All four test samples were used. Charged sample particles, which escaped the corona charger, were observed to experience the electric force from the curtain. This force was of a traveling wave in nature. This force not only supported the particles' weight but also transported them in a preselected direction. Lycopodium particles' motion, under the influence of an electric curtain, excited by six phase ac voltage, is shown in Figure 4. While the total charge on a particle, going through either of the two charging mechanisms described, is related to the particle size [3], the gravitational force is directly proportional to its density. The test samples with larger densities would certainly be more difficult to suspend by the electric curtain. The densities of the test samples are given in Table 1. Up to this point, the electric curtain has been used to act on the charged particles against gravity.

C. Vertical Plane Electric Curtain

It is of interest of conduct an experiment demonstrating the interaction between the repulsion force from a curtain and the charged particles brought toward it by an air drag. Figure 5 shows the system built for the experiment of trapping particles from an air flow. This system was made as airtight as possible. The test sample particles were fed into the opening end of the corona box by an atomizer at one end of the system, and were dragged through the system by an air flow produced by a vacuum cleaner and controlled by a butterfly valve positioned at another end of the system. After

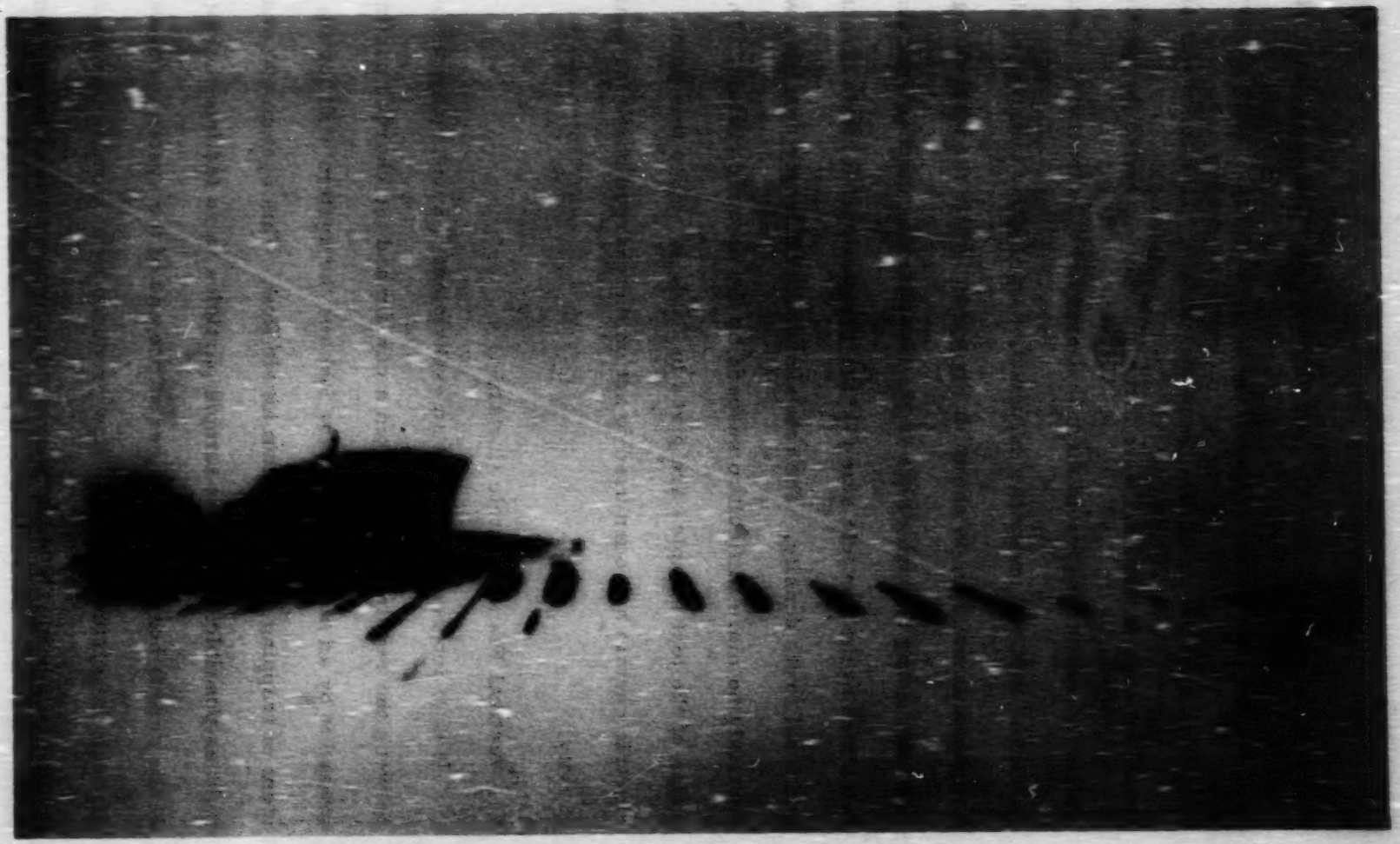


Figure 4. Lycopodium particles suspended by a horizontal planar curtain excited by a 6-phase AC voltage. (Film No. 1)

TABLE 1

Density of Test Substances

Sample	density (g/cm^3)
Lycopodium	1.1×10^{-4}
Water	1
Silicon Monoxide	2.1
Silicon Dioxide	2.2 - 2.7
Flyash	2.2 - 2.6
Feldspar	2.7

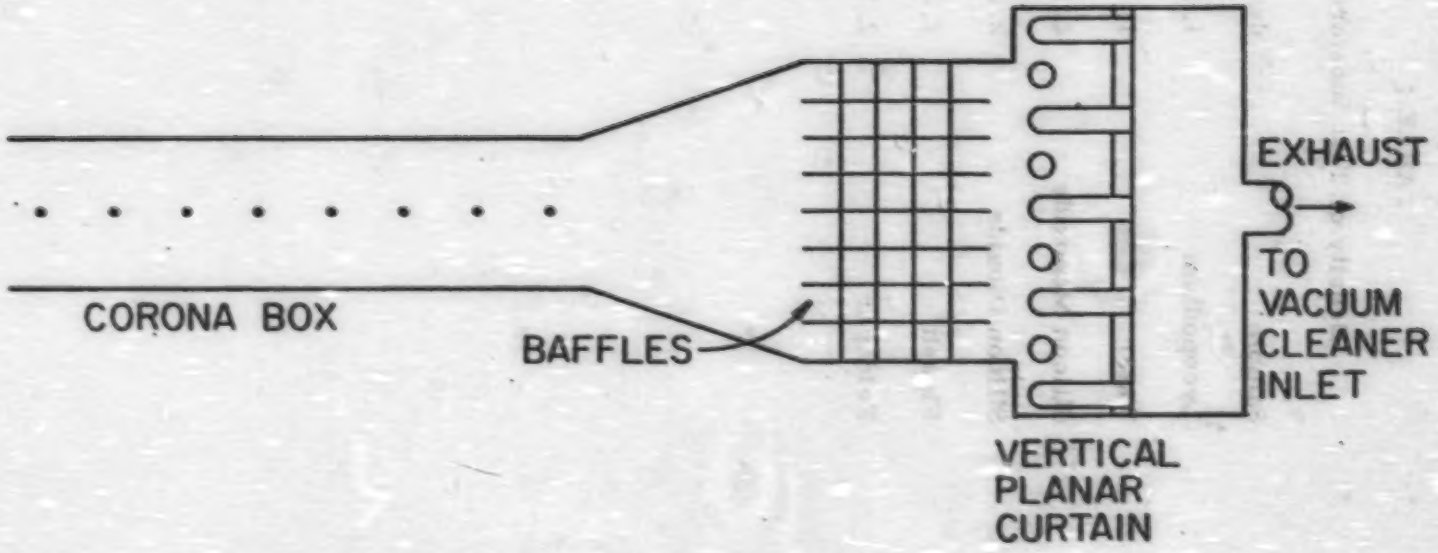


Figure 5. A system with a vertical planar electrostatic curtain. For the experiment of trapping particles from an air flow.

being charged by passing through the corona box, the particles were allowed to see only the uniform portion of the curtain surface which was parallel to the duct cross section connecting the corona box and the electric curtain. The same test materials were used in this system. The flyash was found to be the most difficult one to stop with the vertical electric curtain. The motion of the flyash particles confined to a plane parallel to the surface of a vertical curtain has been recorded, and is shown in Figure 6. These particles disappeared from their confined plane at the instant the curtain voltage was turned off. The highest air flow speed against which the flyash particles could be stopped at the curtain surface was found to be 1.08 cm/sec. Higher air flow speeds would bring flyash particles onto the curtain electrodes.

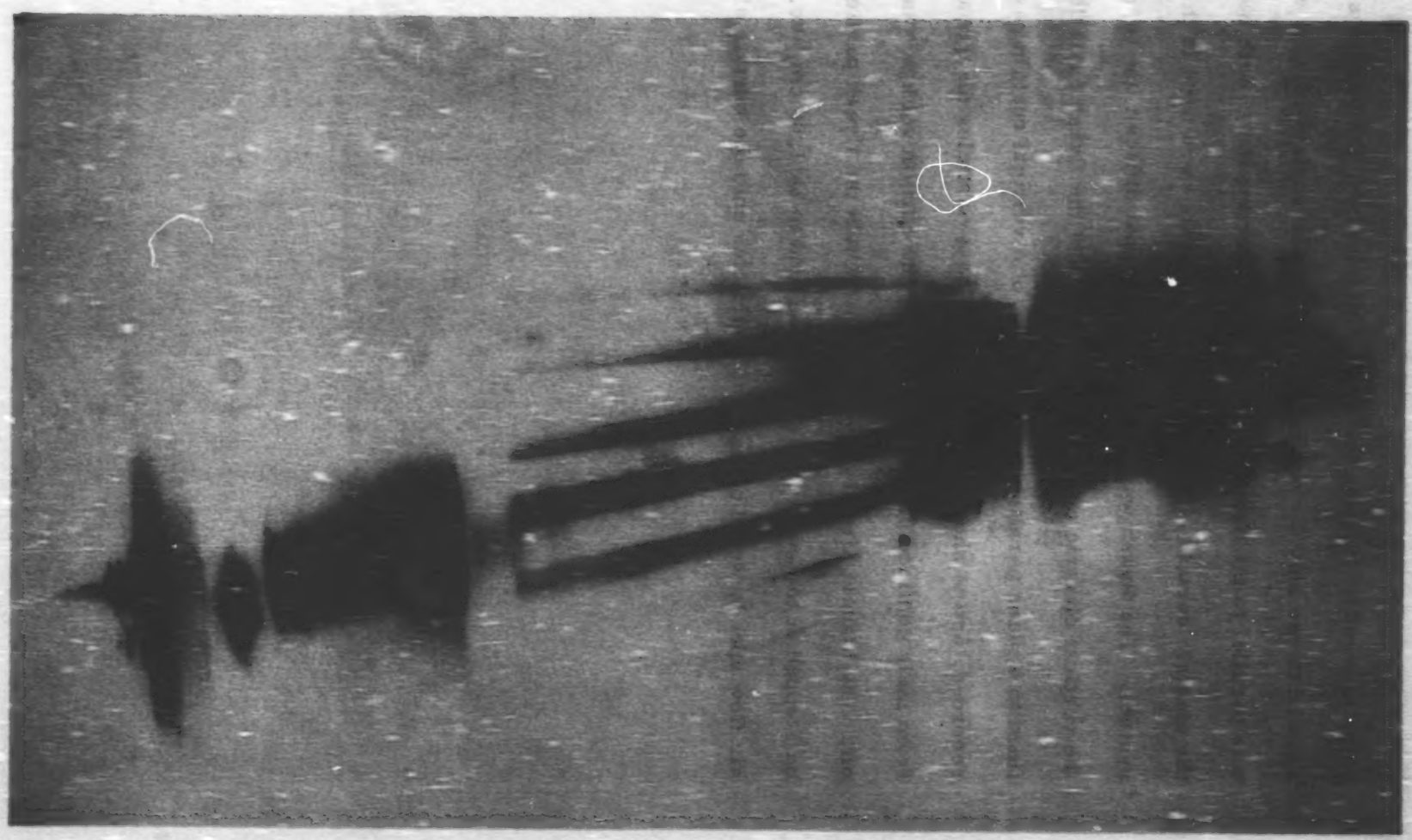


Figure 6. Flyash particles brought toward a vertical planar curtain were confined on a plane in front of the curtain. Planar electric curtain was excited by a 6-phase AC voltage. (Film No. 3)

The inability of the planar curtain to stop more sample particles could be attributed to various effects. First, when the samples were fed to the system, the particles were not very well dispersed; most of them lumped together and formed particle clouds. The charging efficiency of the corona could be much lower than the case in which all the particles were completely dispersed. In the case of flyash, the results were expected to be affected by the fact, reported by Bickelhaupt [8], that the volume conduction process is controlled by an ionic mechanism in which lithium and sodium are the principal charge carriers. Second, the air flow pattern inside the system could be very complicated; the turbulence seemed to be unavoidable, even when baffles were used to regulate the air flow inside a section of the duct connecting the corona charger and the electric curtain. Third, the curtain field was limited by the breakdown value of air.

One way to avoid the third disadvantage was to construct a double curtain; its relative arrangement is shown in Figure 7. The electric field in the space enclosed by the two parallel curtains was stronger due to the superposition of the fields of the individual curtains. Some interesting features have been observed with flyash. Particles were seen in the region having stronger electric fields; they stayed in that region for a few seconds. When the air flow was turned off, with the voltages on the electric curtains left on, thin columns formed by the trapped flyash particles were seen inside the enclosed space, the columns were vertical and parallel to to the curtain rods, and each column was located at the center of the four

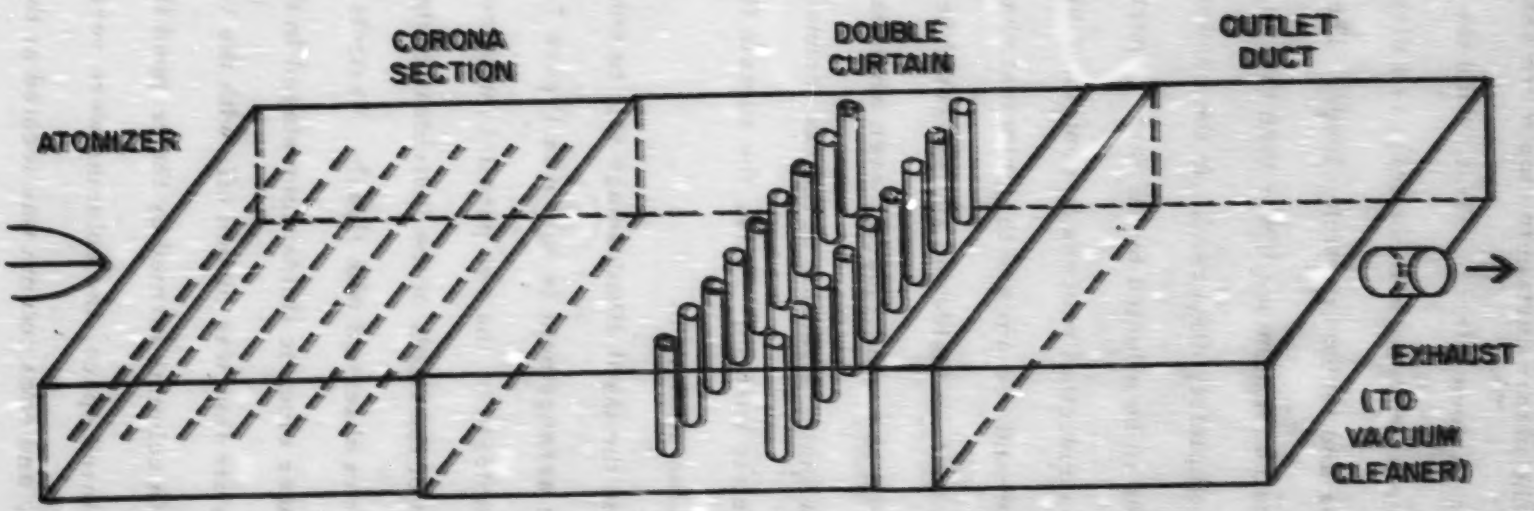
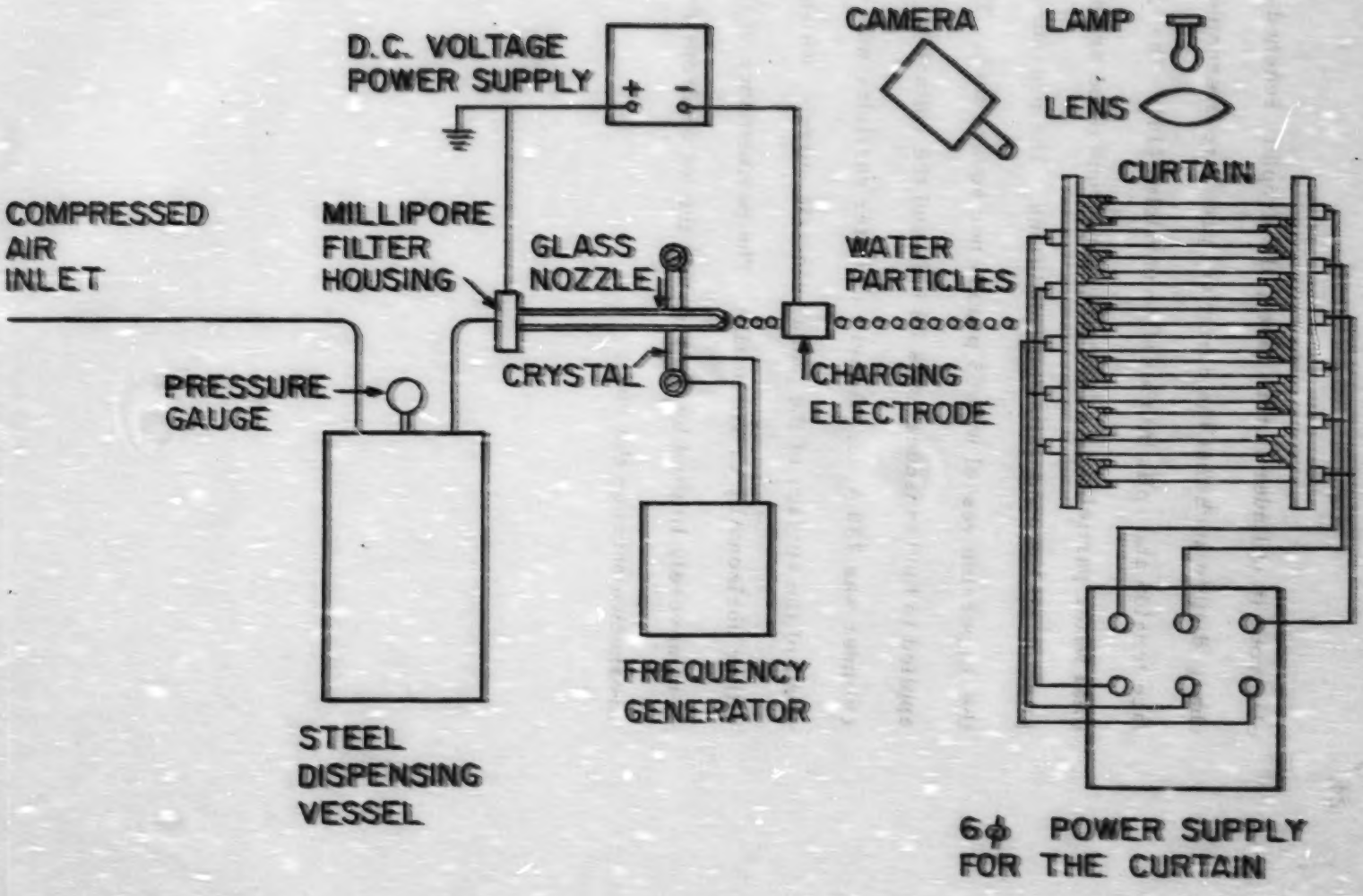


Figure 7. Double curtain system used to trap particles from air flow. Rods with dark and light ends are in opposite polarities.

nearest neighboring rods. However, the performance of the double curtain in stopping particles was very little better than the single curtain.

5. CHARGED WATER PARTICLES AS INTERMEDIATE COLLECTOR FOR FINE PARTICULATE MATERIALS

Water drops can be made highly charged particles. It would be useful if one could use the highly charged water droplets as intermediate collectors for oppositely charged solid particles. If the charge-to-mass ratio of the final compound becomes larger than that of the particle, then the planar electric curtain together with the charged water droplets can be considered a better dust collector. Miller [9] has developed an electric sprayer which is used in painting and coating. This same mechanism was used to generate a water film. The razor-blade sharp edges formed a thin slot from which the water was compressed out. These sharp edges also served as charging electrodes. A sprayer with a slot width of 0.001 in. and length of 2 in. was used, but the result was not promising. The failure was mainly due to machining difficulties in making the slot width smaller than 0.001 in. Another technique has been developed for generating charged water droplets. A glass nozzle with an orifice diameter of 0.0009 in. was made. It was connected to a system shown in Figure 8. Compressed air was applied to the inlet of a steel dispensing vessel containing distilled water; the outlet of the vessel is connected through a millipore filter housing to the glass nozzle which has a very small orifice. The glass nozzel neck was glued with epoxy onto a "PZT Bimorph" crystal. This crystal was excited by a frequency generator and was used as an electromechanical transducer, which broke a continous water jet into a train of water droplets. After passing through a charging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6φ POWER SUPPLY
FOR THE CURTAIN

electrode (a cylinder in this case), the droplets reached a highly charged state such that the electrical pressure overcame the surface tension and split into smaller particles [10]. The size of the final water particles was measured and found to be around 30 μm (diameter) under the following conditions. The pressure inside the dispersion vessel was 55 pounds per square inch. The frequency applied to the transducer was 25 KHz and the voltage on the charging cylinder was 730 V dc. A layer of water particles was suspended in front of the surface of the planar electric curtain, which was positioned either horizontally or vertically. The performance of this curtain was very severely limited by the fact that the water drops caused electrical breakdown between the rods.

6. CONCLUSION

All of the different materials mentioned above have been stopped or transported by the planar curtain to a certain degree with external forces due to either gravity or air drag. The air flow was restricted to about 1-2 cm/sec for particle confinement. Part of the particles passed through the curtain without being affected. The optimum condition for the planar curtain was achieved by improving the insulation between curtain electrodes. Breakdown occured first between the rods at the upper limit of the field strength in air. Because of the wide range of flyash particle sizes and the variation in the composition and specific gravity of the flyash, the experimental observation on the interaction between the planar electric curtain and the charged flyash cannot be used to clarify the results in a general sense. The water drop experiment was severly limited by electrical breakdown and unless some configuration could be designed to overcome this, it does not appear to be a useful technique for droplet collection. A similar experiment, which has been conducted by Pilat [11], has proved that the collection of fine particles by water droplets in a spray scrubber could be substantially increased by electrostatically charging the droplets and particles to opposite polarities.

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